NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED

May 1944 as
Advance [redacted] Report L4E31

PROFILE-DRAG COEFFICIENTS OF CONVENTIONAL AND LOW-DRAG AIRFOILS AS OBTAINED IN FLIGHT

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WASHINGTON

NOTICE

NACA ACR No. L4E31

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ADVANCE CONFIDENTIAL REPORT

PROFILE-DRAG COEFFICIENTS OF CONVENTIONAL AND LOW-DRAG AIRFOILS AS OBTAINED IN FLIGHT

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SUMMARY

The results of flight investigations of the profile drag of several carefully finished conventional and low-drag airfoils are presented. The results indicated that in all cases lower profile-drag coefficients were obtained with the low-drag than with the conventional airfoils over the range of lift coefficient tested and that, for comparable conditions of lift coefficient and Reynolds number, the low-drag airfoils may have profile-drag coefficients which are at least 27 percent lower than the profile-drag coefficients of the conventional airfoils.

INTRODUCTION

A number of flight investigations have been conducted by the National Advisory Committee for Aeronautics during the past several years to determine the profile drag of various conventional and low-drag airfoils. The purpose of this report is to present the principal results of these investigations in order to provide information that may be of assistance in judging the relative merits of conventional and low-drag airfoils.

AIRFOILS TESTED

The various airfoils tested were the NACA 27-212, NACA 35-215, NACA 66,2-2(14.7), NACA 64,2-(1.4)(13.5),

NACA 2414.5, N-22, and two Republic S-3 sections, one 11 percent thick and the other 13 percent thick. These two sections are designated Republic S-3,11 and Republic S-3,13 in this paper. Flight tests of the NACA 64,2-(1.4)(13.5) and the NACA 2414.5 airfoils are reported in references 1 and 2, respectively. The profiles of the airfoils tested are shown in figure 1. The NACA 27-212 and NACA 35-215 airfoil sections were built into panels around the wings of the airplanes on which they were tested. The others were sections of the actual wings of the test airplanes. The arrangement of the test panels and the spanwise positions of the wing sections tested are shown in plan form in figure 2. The airfoil designation NACA 64,2-(1.4)(13.5), which is the test section of the NACA-NAA (North American Aviation, Inc.) compromise low-drag wing, was based on the maximum thickness and on the pressure-distribution characteristics computed from the measured ordinates of the test section. The designation NACA 66,2-2(14.7) was similarly determined.

The NACA 2414.5, Republic S-3,11, Republic S-3,13, and N-22 sections may be classified as conventional airfoils and the NACA 64,2-(1.4)(13.5), NACA 27-212, NACA 35-215, and NACA 66,2-2(14.7) sections, as low-drag airfoils.

All the airfoils tested were carefully smoothed and faired to eliminate perceptible protuberances due to rivets, skin joints, and access doors. Surface waviness, however, was present to various degrees on the different airfoils. Surface waviness was measured by use of a curvature gage of the type shown in figure 3 on the upper surfaces of the NACA 35-215 and Republic S-3,13 airfoils and on the upper and lower surfaces of the NACA 64,2-(1.4)(13.5), NACA 66,2-2(14.7), and Republic S-3,11 airfoils. No waviness measurements were obtained for the other airfoils.

The curvature-gage measurements on the NACA 35-215, NACA 64,2-(1.4)(13.5), NACA 66,2-2(14.7), Republic S-3,11, and Republic S-3,13 airfoils were made with the legs of the gage spaced 1.2, 3.8, 4.0, 4.0, and 3.0 percent of the section chord, respectively. In order to present these measurements on a comparable basis, the measurements on the NACA 35-215, NACA 64,2-(1.4)(13.5), and Republic S-3,13 airfoils were reduced to values d

that a gage would give if the legs were spaced 4.0 percent of the section chord c. This reduction was made to the first order of approximation on the assumption that the readings of a curvature gage were proportional to the square of the leg spacing. The reduced measurements together with the measurements on the NACA 66,2-2(14.7) and Republic S-3,11 sections are presented in figure 4 as plots of d/c against s/c, where s is the distance along the surface from the leading edge. The dashed lines in figure 4 indicate the approximate curvature-gage readings that would be obtained if the surfaces were free of waviness.

It should be pointed out that wing distortion in flight may introduce waviness considerably different from that measured. This effect is probably adverse and may be expected to vary considerably with wing construction.

The destabilizing effect on the laminar boundary layer due to waviness of a given magnitude increases as the chordwise velocity gradient becomes less favorable (or more adverse). The chordwise velocity distribution for the various airfoils at a section lift coefficient c_l of 0.20 have therefore been included in figure 4. The velocity distributions were calculated for the undistorted airfoil profiles by the method of reference 3. The velocity distributions are given as a plot of the ratio U/U_o against s/c, where U is the local velocity outside the boundary layer and U_o is the free-stream velocity.

PROFILE DRAG

The profile-drag coefficients were evaluated from wake surveys of the various airfoils by the method of reference 4 and compressibility corrections were applied as in reference 5. In figure 5 the section profile-drag coefficients c_{d_o} and the corresponding Reynolds numbers R are plotted against section lift coefficient c_l. The Mach numbers of the tests were less than 0.55.

From figure 5 it may be seen that all the low-drag airfoils gave lower profile-drag coefficients than the

conventional airfoils over the range of lift coefficient tested. The lowest profile-drag coefficient, a value of 0.0040, was measured on the NACA 27-212 section at a lift coefficient of 0.28 and a Reynolds number of 7.4×10^6. The NACA 27-212 airfoil, however, is not considered a particularly desirable airfoil because, as indicated by wind-tunnel tests, low drag is obtained only over a relatively small range of lift coefficient and the pressure gradient at the trailing edge is unnecessarily severe. At Reynolds numbers in the range from 15×10^6 to 20×10^6, now commonly encountered by fighter-type aircraft, profile-drag coefficients of 0.0045 and 0.0052 were measured on the NACA 66,2-2(14.7) and NACA 64,2-(1.4)(13.5) airfoils, respectively. At Reynolds numbers from 22×10^6 to 31×10^6, a profile-drag coefficient of 0.0049 was obtained on the NACA 35-215 airfoil.

The lowest profile-drag coefficient obtained on the conventional wing sections was 0.0062 and was measured on the Republic S-3,11. The lowest profile-drag coefficients obtained on the other conventional sections were 0.0067 for the Republic S-3,13 and 0.0066 for the NACA 2414.5. All these values were obtained at low lift coefficients in the range of Reynolds number from 15×10^6 to 20×10^6. On the N-22 section only one value of profile-drag coefficient, 0.0070, was obtained, which was at the relatively high lift coefficient of 0.50 and the low Reynolds number of 4.4×10^6.

The results for the NACA 66,2-2(14.7) and Republic S-3,11 sections were obtained for the most nearly comparable test conditions - that is, lift coefficient, Reynolds number, and wing-surface preparation - and are therefore best suited for the comparison of the profile-drag characteristics of low-drag and conventional airfoils. At a lift coefficient of 0.20 and a Reynolds number of 16×10^6 the profile-drag coefficients for the NACA 66,2-2(14.7) and Republic S-3,11 sections were 0.0045 and 0.0062, respectively. The profile-drag coefficient of the NACA 66,2-2(14.7) section is thus 0.0017, or 27 percent, lower than the profile-drag coefficient of the Republic S-3,11 section.

Unpublished tests in the NACA two-dimensional low-turbulence pressure tunnel of a section approximating

the NACA 66,2-2(14.7) indicated a profile-drag coefficient of 0.0034 at a lift coefficient of 0.20 and a Reynolds number of 16×10^6. Similar tests (unpublished) of NACA 230-series airfoils indicated a profile-drag coefficient of 0.0063 for an NACA 23011 section at a lift coefficient of 0.20 and a Reynolds number of 9×10^6. The Republic S-3 sections have pressure-distribution characteristics that are very nearly those of the NACA 230-series sections and may therefore be expected to have the same drag characteristics. Inasmuch as the surfaces of the NACA 66,2-2(14.7) airfoil tested in flight were carefully finished to give a very low degree of waviness (figs. 4(g) and (h)), probably comparable with that of the tunnel model, the considerably greater drag measured in flight as compared with the value obtained in the tunnel is believed to be due to an increase in surface waviness associated with wing distortion under air loads. The better agreement between the flight and tunnel results for the conventional sections may indicate that the position of transition is so far forward on these sections that it is not materially affected by an increase in surface waviness resulting from loads imposed on the wing in flight.

CONCLUDING REMARKS

The results of profile-drag tests of various smoothed airfoils indicated that in all cases lower profile-drag coefficients were obtained on low-drag airfoils than on conventional airfoils over the range of lift coefficient tested. The results also indicated that, for comparable conditions of lift coefficient and Reynolds number, the low-drag airfoils may have profile-drag coefficients which are at least 27 percent lower than the profile-drag coefficients for the conventional airfoils.

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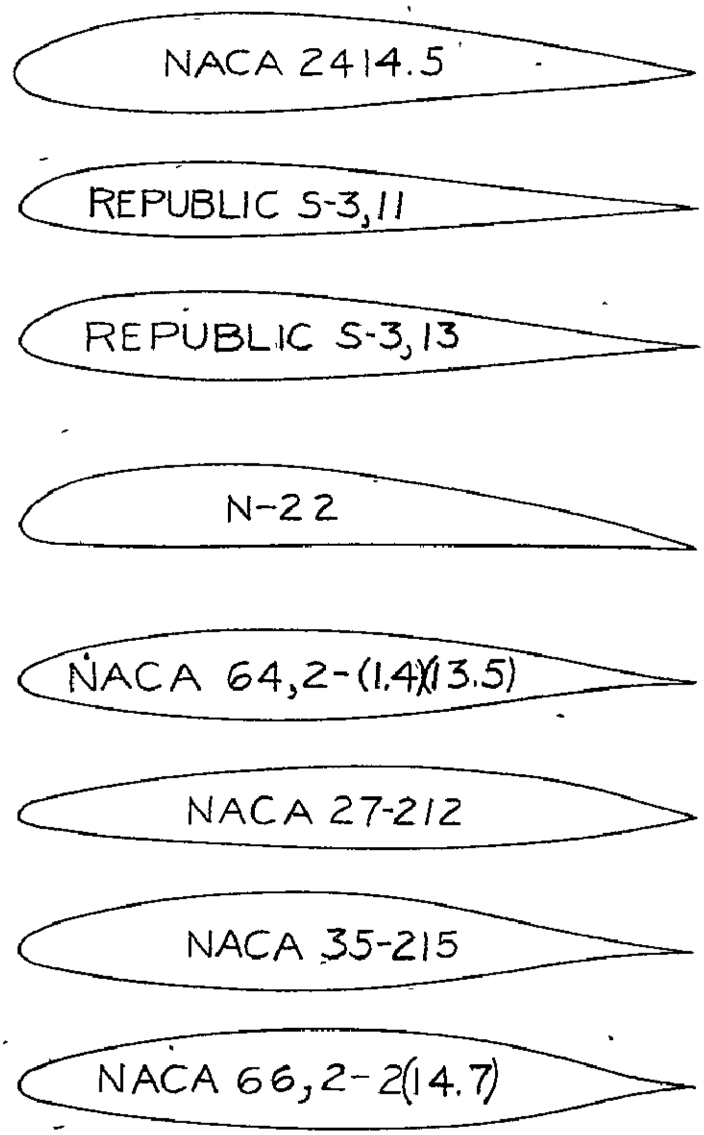

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Figure 1.- Profiles of various airfoil sections tested in flight.

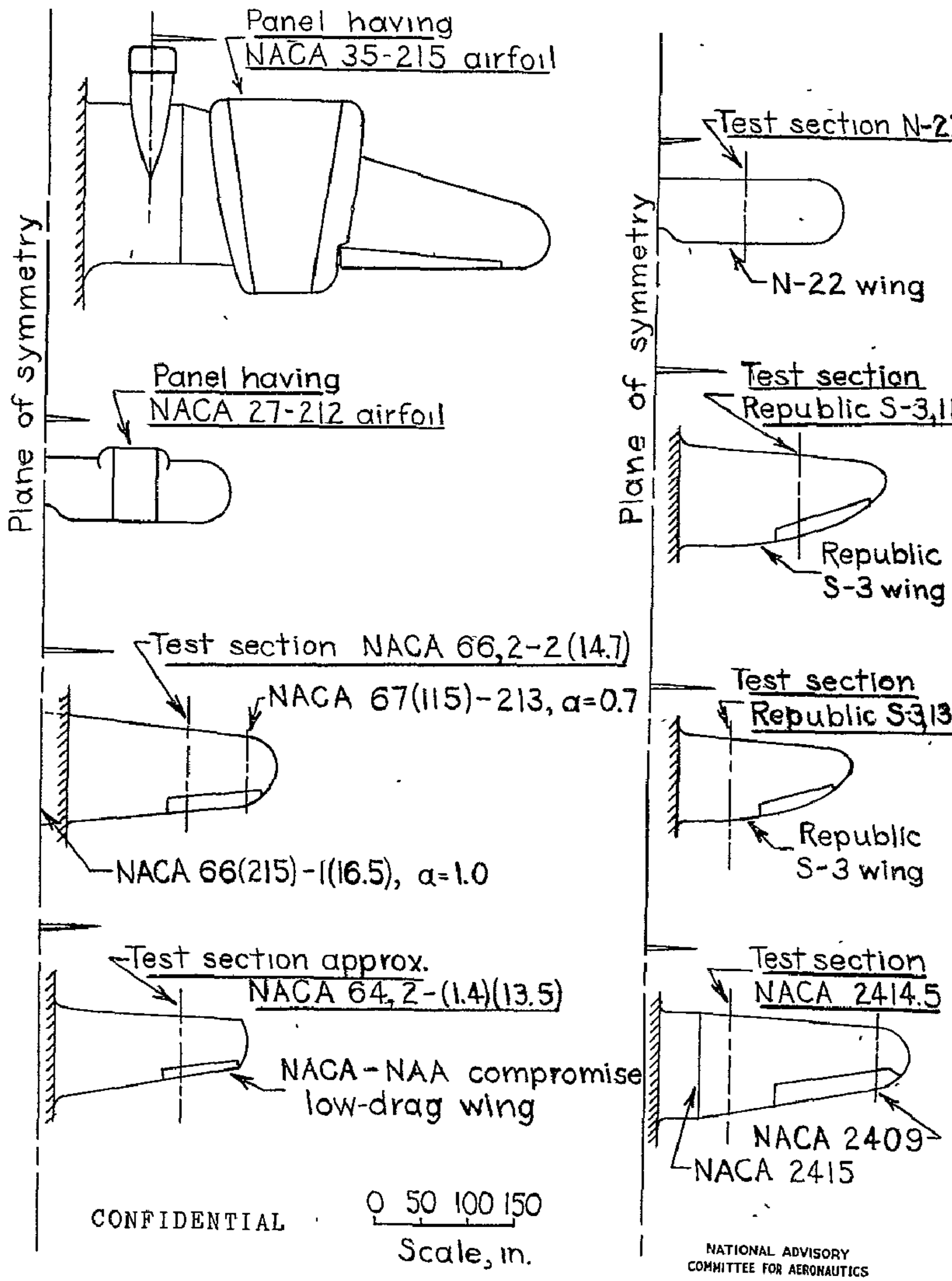

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Figure 2.- Plan forms of various wings of which tests were made.

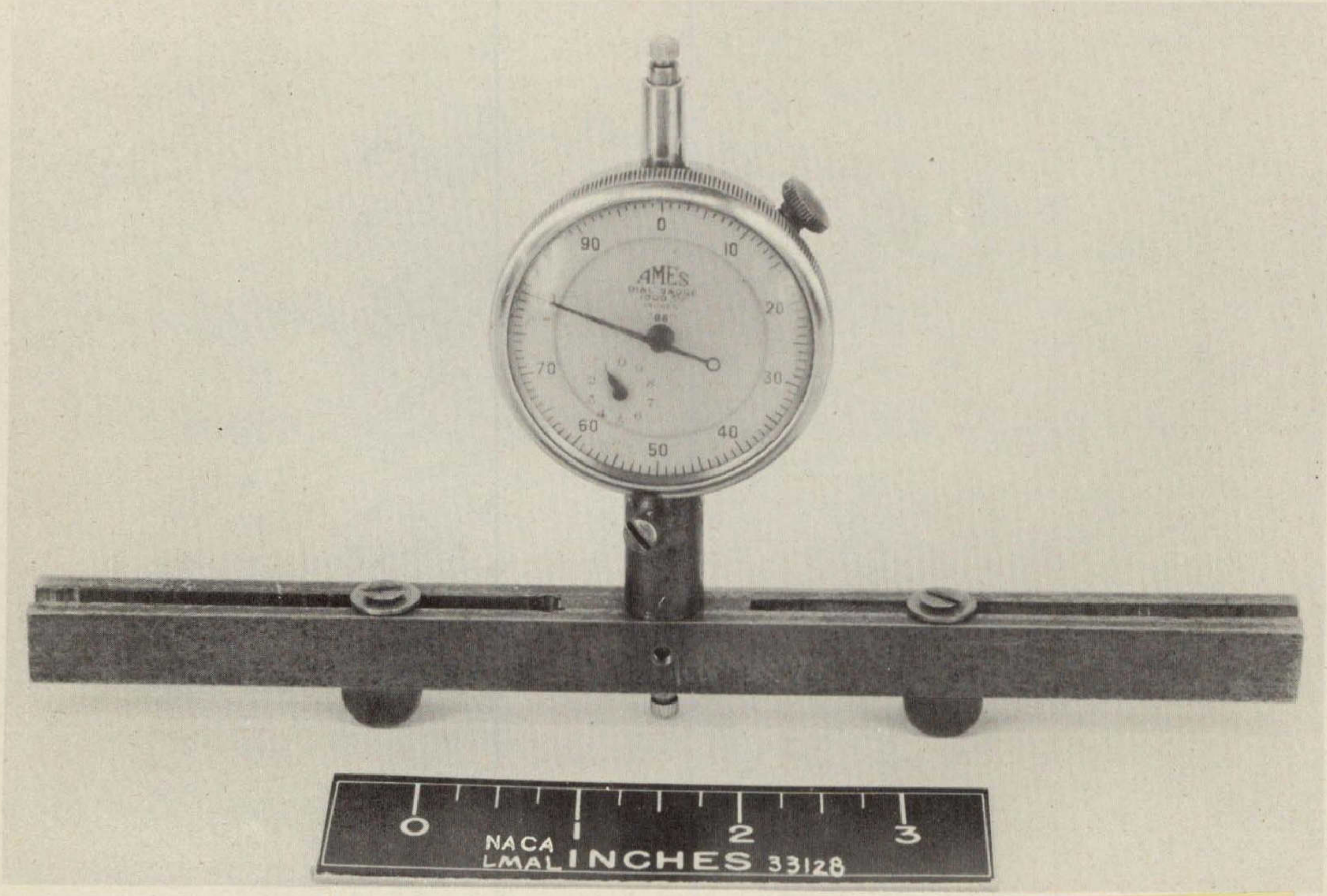
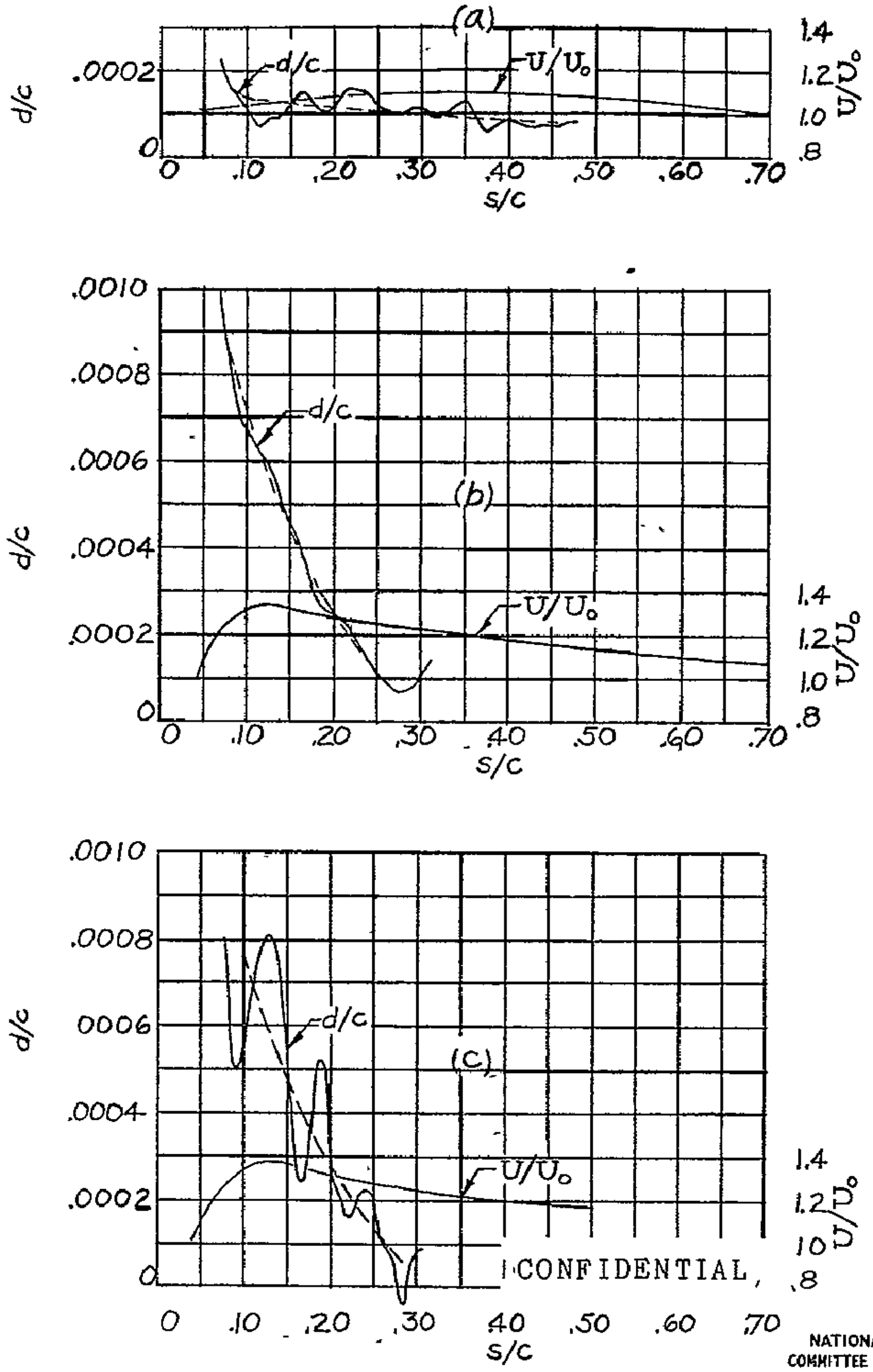


Figure 3.- Curvature gage.



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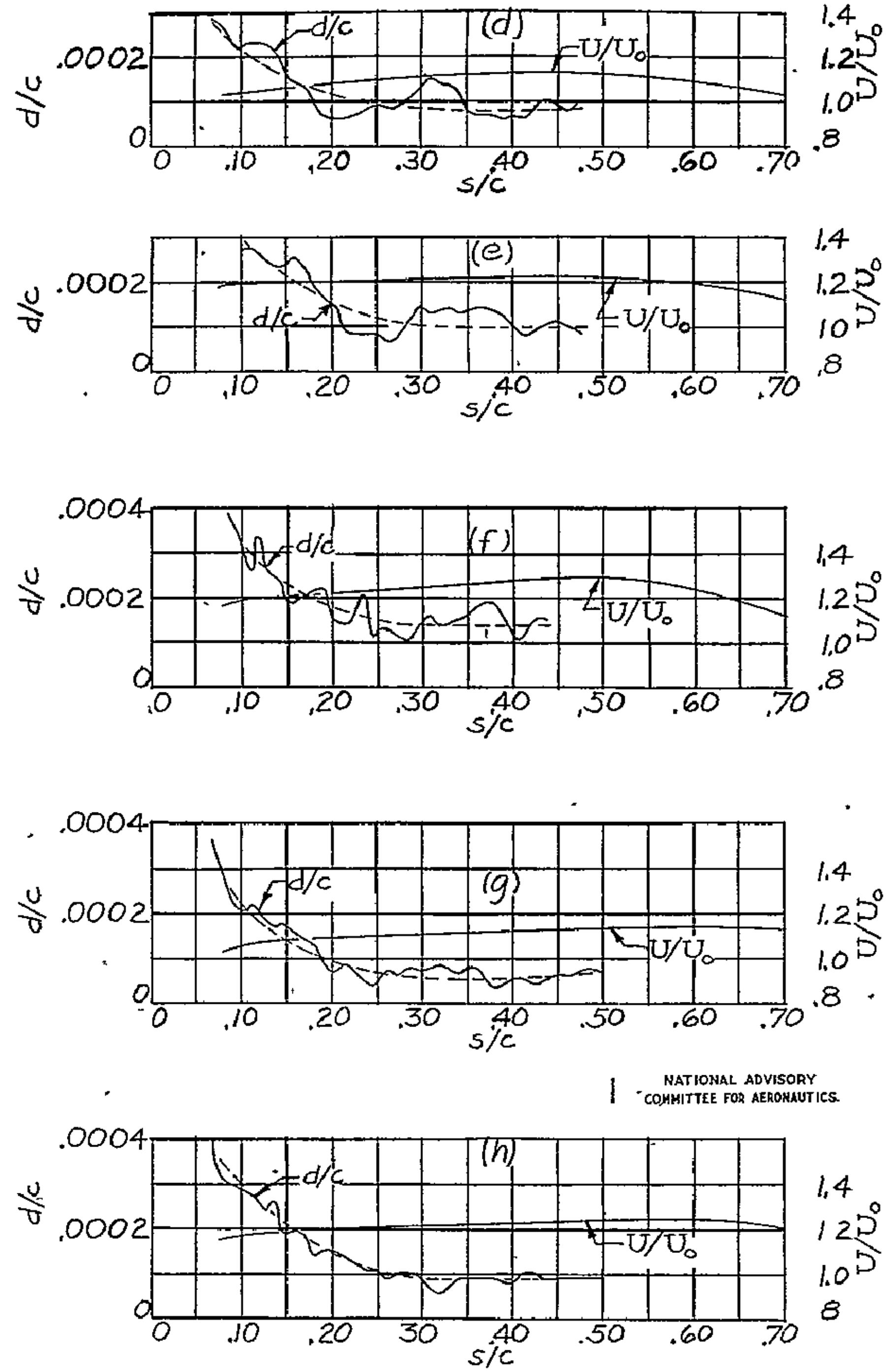
(a) Republic S-3,11 airfoil, lower surface.
(b) Republic S-3,11 airfoil, upper surface.
(c) Republic S-3,13 airfoil, upper surface.

Figure 4.- Surface waviness and velocity distribution (at c_l = 0.20) over various airfoils. (Dashed lines indicate approx. gage readings for surfaces free of waves.)



(d) NACA 64,2-(1.4)(13.5) airfoil, lower surface.
(e) NACA 64,2-(1.4)(13.5) airfoil, upper surface.
(f) NACA 35-215 airfoil, upper surface..
(g) NACA 66,2-2(14.7) airfoil, lower surface.
(n) NACA 66,2-2(14.7) airfoil, upper surface.

Figure 4.- Concluded.

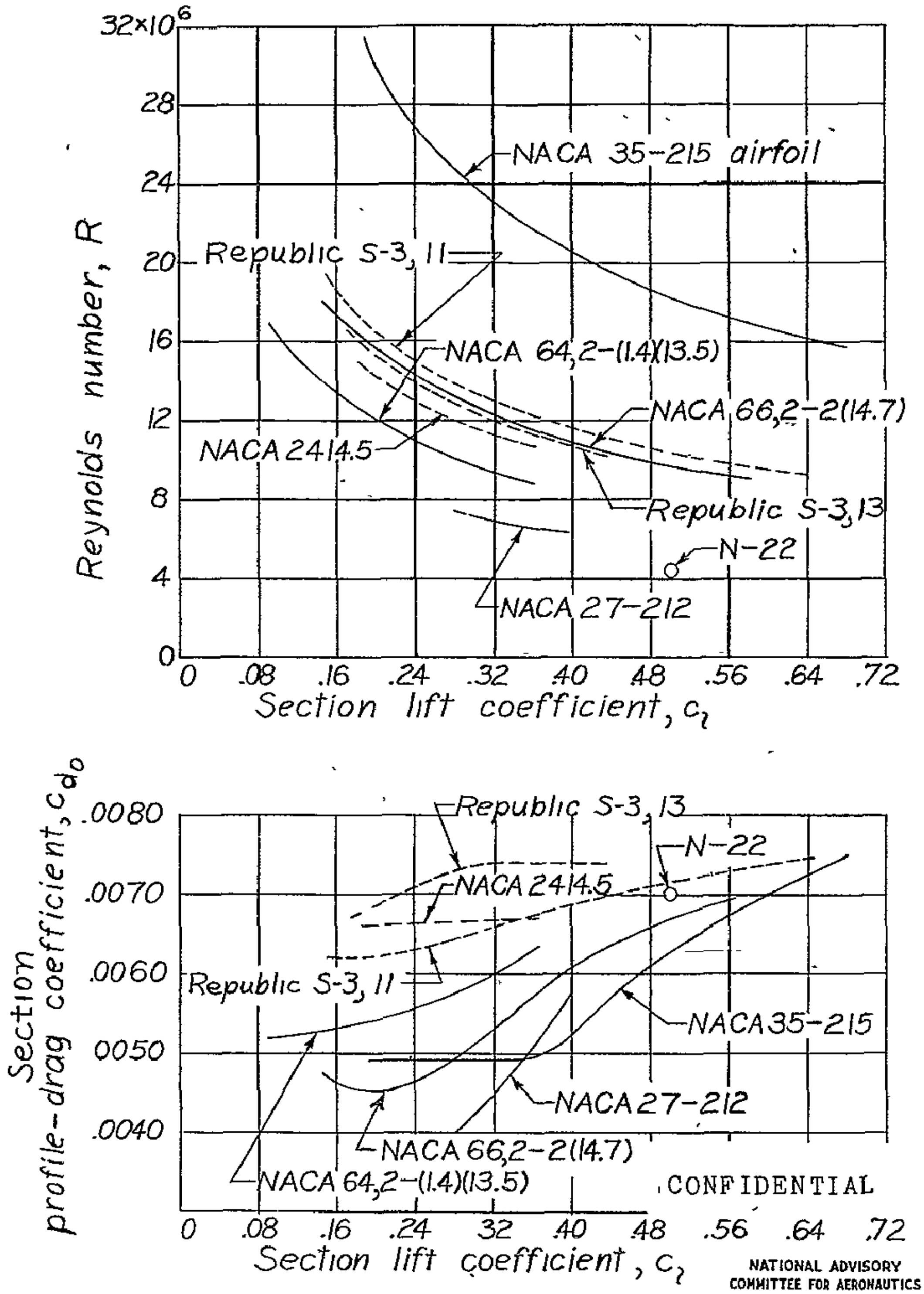


Figure 5.- Comparison of profile-drag coefficients obtained in flight on various conventional and low-drag airfoils. Reynolds number for corresponding lift coefficients given above.